ASD

APOLLO SYSTEMS DEPARTMENT

GENERAL ⊛ ELECTRIC

HOUSTON, TEXAS	TECHNICAL INFORMATION RELEASE	TIR 741-MED-4014

FROM	TO
J. I. Leonard, Ph.D.	J. A. Rummel, Ph.D./DB6

DATE 7/17/74	WORK ORDER REF: MA-252-T	WORK STATEMENT PARA: NAS9-12932	REFERENCE:

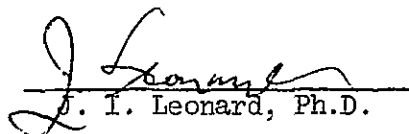| SUBJECT	Modifications to the Steady-State 41-Node Thermoregulatory Model Including Validation of the Respiratory and Diffusional Water Loss Equations

This report discusses some modifications to the steady-state version of the thermoregulatory model. These include conversational mode of operation, greater choice of output variables, increased efficiency of convergence, and greater flexibility for performing parameter estimation. In addition the equations for respiratory and skin diffusion water losses have been improved and validated. Some recommendations for further experimental and computer studies are also included.

J. I. Leonard, Ph.D.

Attachment
/db

CONCURRENCES		
Counterpart:	Medical Projects Unit Manager: R.C.Croston	Engrg. & Advanced Programs Subsection Mgr. J.W.Fulcher

DISTRIBUTION NASA/JSC: Retha Shirkey/JM6(1979) GE/TSS:

P. Hogan,Ph.D.	C.Sawin, Ph.D.	L.J.Fitzjerrell	G.T. Archer
J. Waligora	M. Buderer, Ph.D.	R.F.Hassell	CP File
G. W. Hoffler,M.D.	P. Schachter,Ph.D.	D.J.Grounds	
A. Nicogossian, M.D.		V.J.Marks	

Page No. 1 of 1

ASD 4028

TABLE OF CONTENTS

MODIFICATIONS TO THE STEADY-STATE 41-NODE THERMOREGULATORY

MODEL INCLUDING VALIDATION OF THE RESPIRATORY

AND DIFFUSIONAL WATER LOSS EQUATIONS

1.0 INTRODUCTION

After the simplified version of the 41-Node Stolwijk Metabolic Man Model was implemented (References 1 and 2) on the Sigma 3 and UNIVAC 1110 computers in batch mode, it had become desirable to make certain revisions. First, the availability of time-sharing terminals makes it possible to provide the capability and flexibility of conversational interaction between user and model. Secondly, recent physiological studies have shown the need to revise certain parameter values contained in the model. Thirdly, it was desired to make quantitative and accurate predictions of evaporative water loss for humans in an orbiting space station. This required that the model be carefully validated with available experimental data and improved if necessary. It was decided to initiate these revisions with the steady-state model because of the speed of response of that algorithm and also because much of the available data was collected under steady-state conditions. This report is the result of the first phase of this effort.

2.0 MODIFICATIONS TO THE THERMOREGULATORY MODEL

A. Demand Terminal Use

Conversion of the mode of execution from batch to demand (time-share) terminal use was made. The demand mode of execution now includes a conversational flow of I/O in which the program

prompts the user at a remote terminal to modify input parameters and output listing (Reference 3).

B. New Output Listings

The output listing has been changed to include those variables related to evaporative water loss. In addition, it is also possible to obtain a listing of: a) important body and undergarment temperatures, b) distribution of blood flows, c) heat balance terms, d) terms relating to the temperature controller system. Examples of these various output listings are given in a user's guide (Reference 3).

C. New Convergence Algorithm

A new subroutine, CONVRG, has been added that greatly improves the reliability and efficiency of the steady-state convergence algorithm. The original method of solution by successive substitution (Reference 4) was left essentially intact, but it is now incorporated into CONVRG. Convergence by this method alone failed to occur in a great many cases. Further investigation showed that failure to converge was caused by an overshoot of the error criteria. For example, instead of converging on a near-zero value of body heat storage rate, successive values of STORAT might be -10, -5, -1.5, +3, +5, thus completely overshooting the steady-state error criteria of 0.0 ± 1 BTU/hr. Apparently, there is no guarantee for convergence using this method unless a specific "homing" technique is used. The simplest method that can insure convergence in this case is the half-interval method (Reference 5).

This algorithm determines when the value of STORAT changes sign (i.e., crosses the null point), adjusts the temperatures for values exactly in between those corresponding to either side of the null point and determines a new value for STORAT by cycling through the model one time. If this new value of STORAT is still not within the error boundaries, the temperatures are again averaged and changed in a direction that will produce convergence. Each application of the iterative scheme reduces by half the length of the STORAT interval known to contain the null point. The number of half-interval iterations, n, required to locate the error boundaries is given by:

$$n = \frac{\ln(\Delta_1 / EPSI)}{\ln 2}$$

where Δ_1 is the length of the starting interval and EPSI is the length of the error interval.

While the half-interval method will insure convergence once values for STORAT are found on either side of the null point, there is still no guarantee that the method of successive substitution will locate the null point within the maximum allowable number of iterations NMAX (normally set to 500). If this occurs a message "CONVERGENCE NOT OBTAINED" will be printed. The user then has two options to try to obtain a satisfactory solution: a) the value for NMAX can be increased and/or, b) the value for EPSI can be increased. If convergence is still not obtained, or if the user desires to determine the behavior of

STORAT during the convergence process, the system input parameter DEBUG should be set to 1.0. This action will cause a printout of each successive value of STORAT, NCOUNT and T(1), the latter two being the number of iterations and the head core temperature respectively. Non-convergence will only occur in a very small fraction of cases and in most of those situations, the DEBUG procedure will reveal a value of $STORAT_o$ not very far from zero that will usually yield a satisfactory solution. The value of EPSI can then be set to include that solution (i.e., set EPSI = $STORAT_o$) and the program can be rerun with DEBUG set back to 0.0. The procedure for manipulating NMAX, EPSI and DEBUG can be found in Reference 3.

D. <u>Revised Values for Model Parameters</u>

A recent study by Dr. Stolwijk (Reference 6) reports values for certain parameters of the thermoregulatory model that are different from values that he previously published (References 7, 8). Those earlier values were used by Lockheed and General Electric to initialize the thermoregulatory model (References 1, 2, 9), and have now been revised in accordance with the new Stolwijk study. Specifically, values for the following parameters have been changed: TSET (set-point temperatures), C (heat-capacity), BFB (basal blood flow), QB (basal metabolic rate), FACTOR (thermal conductivity), SKINR (skin temperature receptor density), and CHILM (muscle weight distribution). Each of these terms represent a vector of values for the various segments of the body. Not all of the vector elements necessitated

a revision. In addition, Stolwijk recommended a change in all
of the twelve controller constants (i.e, CSW, SSW, etc.) and
these have also been implemented. The latest values for these
terms (in English units) can be found in the program listing
attached to the user's guide (Reference 3).

E. Revised Controller Equations

Stolwijk's final report (Reference 6) also contained a revised
form of the controller equations and these have been implemented
in the current version of the steady-state model. The new
equations are listed on lines 43-86 of Subroutine MAN (See
Reference 3). Lines 49-50 calculates the deviation or error
from set point of the temperatures of each compartment (ERROR(N)),
although only the skin and headcore compartments are used in
future calculations. The thermoreceptor error signals from
the skin compartments are then integrated (lines 51-67) accord-
ing to whether they came from hot (WARMS) or cold (COLDS)
receptors and are weighted with respect to the receptor density
of each compartment. The controller equations (Lines 70-74)
determine the efferent outflow signal from the hypothalamic
thermal controller based on a function of ERROR(1), WARMS and
COLDS as well as 12 controller constants. The form of these
equations are somewhat different than in the original version.
The first term of each equation is proportional to the ERROR
value of the had core and is now able to assume both positive
and negative values. The second term used to be a function of

either WARMS or COLDS, but in the new version this term is a
linear combination of both of these factors. Lines 78-86
protects each of the four efferent signals from becoming nega-
tive. Dr. Stolwijk does not explain why this formulation of
the thermal controller is superior than that used in the original
model. It is not clear, for example, why the output of the cold
skin receptors (COLDS) should act to increase the value of the
SWEAT command rather than decrease it. Nevertheless, he does
show that the resulting behavior of the model's simulation
agrees rather well with experimental observation.

F. Correction of Errors

Several errors were discovered in the steady-state model that
were associated with inappropriate conversion factors. These
resulted from translating the original Stolwijk formulation of
the model which was in metric units to a model using
English units. The first of these errors appears in the calcu-
lation of the sweating rate:

sweat rate from = SKINS(I)*SWEAT*2**(T(J) - TSET(I))/4
skin segment I

where SKINS represents the relative density of sweat glands and
SWEAT is the value of the efferent command from the hypothalamic
controller. The exponential term describes the empirical obser-
vation that for every 4 degree rise in local skin temperature
the sweat rate doubles. The equation was originally written in
metric units in which temperatures were in $^{\circ}$C. However, when

the program was converted to English units the factor "4" was

unchanged instead of being replaced by $4 \times 1.8 = 7.2$ F^o. In a

later paper Stolwijk revises this figure from 4 C^o to 10 C^o and

therefore the appropriate new value in English units is

$10 \times 1.8 = 18$ F^o.

A second unit conversion error appears in the equation describing

muscle blood flow:

$$BF(N+1) = BFB(N+1) - QMET(N+1) - Q3(N+1)*QBASAL$$

where BFB = basal blood flow and (QMET - QB*QBASAL) = heat pro-

duction in muscle compartments due to work and shivering.

Stolwijk originally wrote this equation in metric units in which

blood flow was in units of liters/min and heat production was in

units of kcal/min. The heat terms were multiplied by an implied

conversion constant whose value is 1.0 and whose units must be

liters blood/kcal. This assumes that arterial blood normally

contains 0.2 liters oxygen/liter blood, that 5 kcal energy are

produced for each liter of oxygen consumed and that all oxygen

in arterial blood is removed and consumed by the muscle. In that

case one liter of blood can produce $0.2 \times 5 = 1.0$ kcal energy.

The equivalent conversion constant in English units is 0.572 lbs

blood/BTU rather than 1.0. The assumption that arterial blood

has been stripped of all its oxygen is only approximately correct

for very exhausting exercise. For conditions of rest only about

30% of the arterial oxygen is removed. Hence, it would take

about $100/30 = 3.33$ times as much blood at rest to provide the

oxygen to provide 1 BTU of energy, i.e., the conversion constant at rest should be 3.33 x .572 = 1.9 lbs blood/BTU. The equation above could be written as:

$$\underset{\text{lbs/hr}}{\text{muscle blood flow}} = \underset{\text{lbs/hr}}{\text{basal flow}} + \underset{\text{BTU/hr}}{\text{heat produced by working}} \times \underset{\text{lbs/BTU}}{K}$$

where K varies from 1.9 at rest to 0.57 at exhaustive exercise. The effect of various values of K on the total body blood flow rate over a range of work loads is shown in Figure 1. It can be seen that the cardiac output as simulated with the model using a value of K = 0.77 agrees very well with the experimental data over the entire range. Note that when K = 1.0 there is increasing deviation from the data at the higher work loads. It was decided to use a value of K = 0.77 as the conversion factor.

Several other errors have been uncovered which appear to be merely transcription errors in preparing the program for the Sigma 3 and UNIVAC 1110. They are contained in the equations for the heat transfer coefficients: 1) the equation for the forced convection evaporation coefficient, HE, contained the term SQRT(VCAB*PCAB) which has now been changed to SQRT(VCAB/PCAB) (see Reference 9, p.2.32 and Reference 10, p.83); 2) the equation for the free convection evaporation coefficient, HE1, was missing a pair of parenthesis around the term (TUG(I) - TCAB); 3) the equation for the free convective heat transfer coefficient, HC1, includes a temperature difference term raised to the 0.25 power. Berenson, in his chapter in
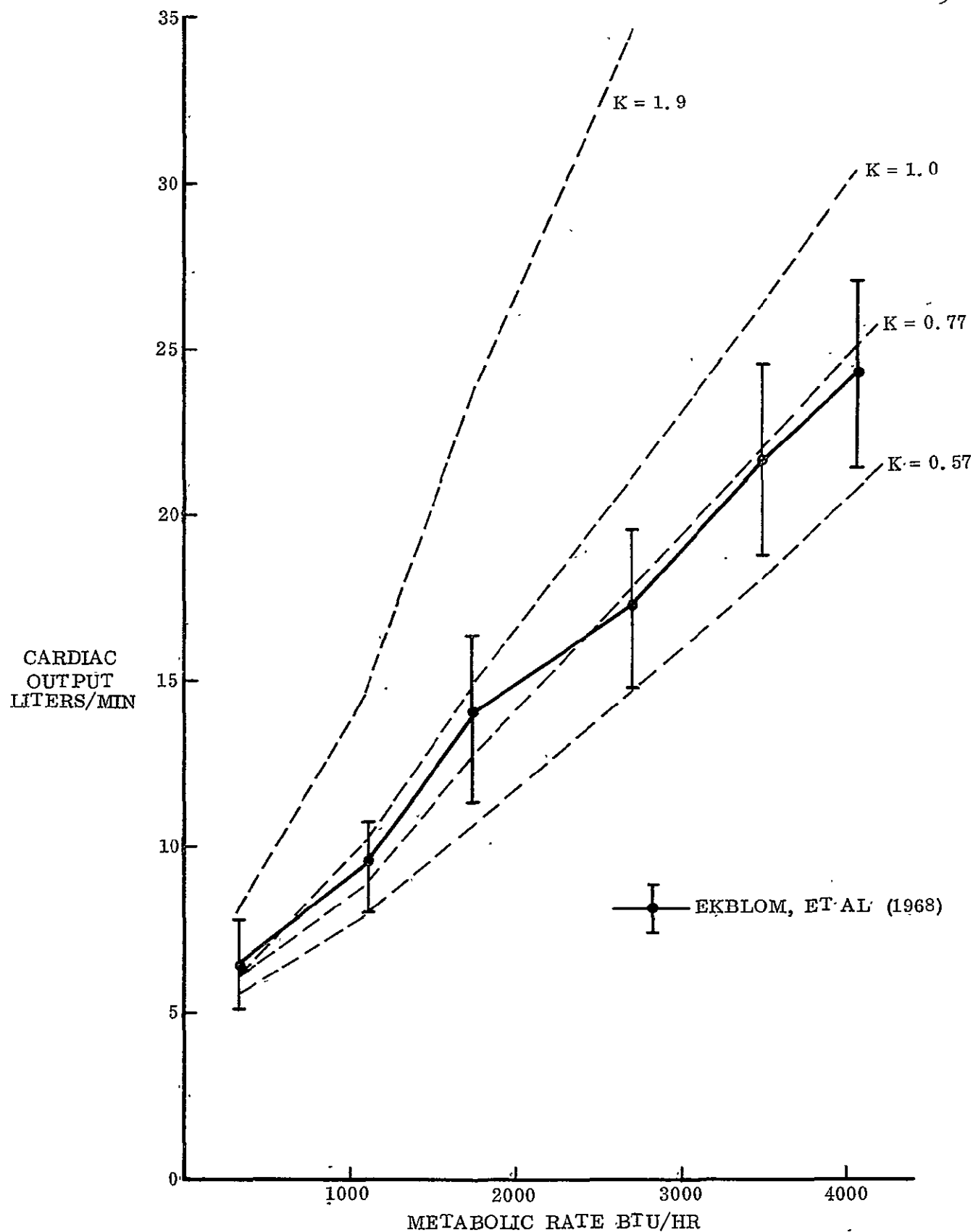
FIGURE 1

Effect of metabolic rate on cardiac output. The parameter K represents the amount of blood (lbs) required to deliver the proper amount of oxygen which, when consumed by the tissues, produces the equivalent of one BTU of energy.

Reference 10 gives the same equation raised to the 0.5 power.

However, similar equations in McAdams (Reference 11) and

Chapman (Reference 12) show that free convection in the laminar

and turbulent range require an exponent of 0.25 and 0.33,

respectively. Hence, the use of the exponent of 0.25 is prob-

ably correct and was not changed in the program; 4) A consid-

erable number of equations and terms were found that were

computed, but never used elsewhere in the program. These were

apparently not removed when the model was converted from the

spacesuit mode to the shirtsleeve mode. A general clean-up of

the program resulted in the deletion of the following terms:

SQW, SCABC, SCAB1, SWTFAC, WARMM, COLDM, QLCG, AND VEFF.

3.0 REVISION AND VALIDATION OF EVAPORATIVE LOSS EQUATIONS

There are three routes for water evaporation from the body considered

by the model: respiratory water loss, diffusion through the skin,

and sweating. The equations describing all of these processes have

been revised to some extent either because a more physiologically

meaningful approach was available or because validation of the model

with experimental data revealed that the original equations were not

a good representation of reality.

A. Diffusion of Water Through Skin

There have been few studies that attempt to measure skin diffu-

sional losses at the exclusion of other body water losses,

especially over a wide range of temperature, humidity, air

velocity and pressure. Intuition suggests that these environ-
mental parameters should affect skin diffusion of water. One
study that provides a basis of comparison for validating the
diffusion equation has been reported by Carleton and Welsh
(Reference 13). Figure 2 shows a portion of the results of
their study regarding evaporation from the skin under non-
sweating conditions at two ambient pressures and over a range
of temperatures, humidities and air velocities. The diffusion
equation in the original model (Reference 1,9) did not make
provisions for the effects of barometric pressure and air vel-
ocity. In addition, the coefficient for diffusion appears to
be too high. This is reflected in Figure 2 (a,b) by the dis-
crepancy between simulated and experimental results. A more
accurate representation of the data has been obtained by the
following proposed equation for skin diffusion:

$$QDIF(I) = 2.8 * ACE(I) * (VPP(TUG(I) - VAPPUG) * (VCAB/PCAB)^{0.15} \quad (1)$$

where VCAB and PCAB are the air velocity (ft/min) and barometric
pressure (lbs/in^2) respectively, ACE is the convective surface
area of body element I and (VPP(TUG(I) - VAPPUG) is the water
vapor pressure difference between the clothing (assuming satur-
ation at the clothing surface temperature) and the environment.
It should be noted that the data has been obtained from studies
of almost nude subjects, while equation (1) is supposed to
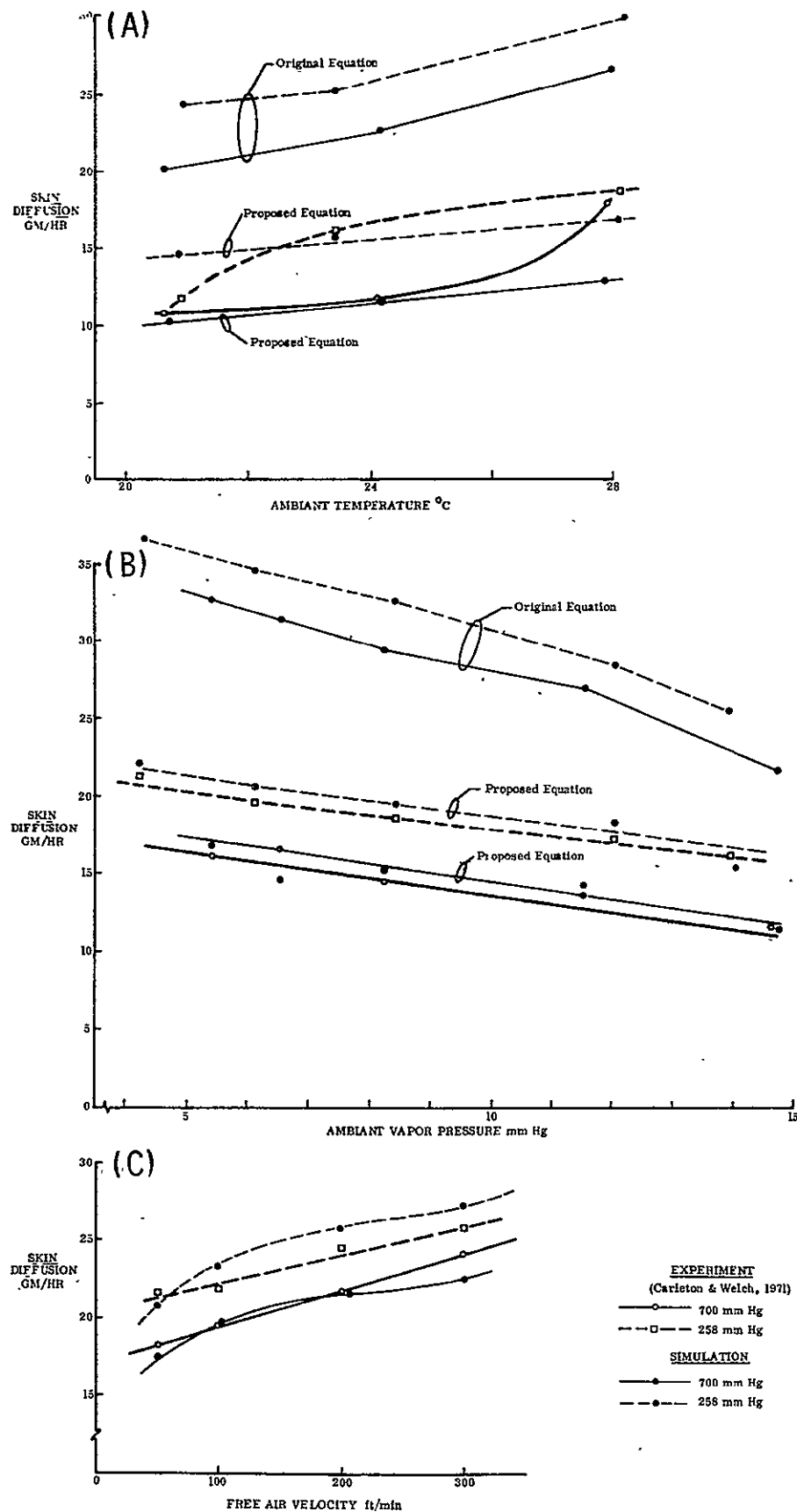represent the diffusion from nude or clothed individuals.

FIGURE 2

Skin diffusion evaporative rate in resting subjects as a function of ambiant temperature (A), ambiant vapor pressure (B) and free air velocity (C). Comparison is made between experimental and simulated results. Figures 2A and B compare results between the original equation for diffusion and the equation proposed in this report.

Hence, the accuracy of the equation has not been tested for subjects who are fully clothed. In addition, the air velocity over which this equation has been tested ranges from 20 to 300 ft/min and extrapolations outside of this range must be viewed with caution, especially at the low range when natural convection might play a significant role. Nevertheless, in the range considered it is apparent that the proposed equation for diffusion is superior to the original formulation.

Two other changes to the diffusion process have been made. First, it has been suggested that the maximum value of skin diffusion is not more than 6% of the associated maximum possible evaporation rate (Reference 14). This observation has been incorporated into the present model by letting QDIF(I) = 0.6*EMAX(I) if QDIF, as calculated by Equation (1), is greater than 6% of EMAX. Secondly, it has been recognized that the water diffusion through the skin and active sweating never occur on the same skin area at the same time (Reference 14). Thus, QDIF(i) for a body element is at its maximum when sweat secretion, QSWT(I), is zero, and QDIF(I) will approach zero when QSWT(I) = EMAX(I) or when the surface is 100% wet. This has been implemented in the program by computing the wet fraction of each body surface element:

$$WTAREA(I) = QSWT(I)/EMAX(I) \tag{2}$$

(although it is possible for WTAREA(I) to have values above 1.0 it is physiologically meaningless for it to do so and the

program automatically limits WTAREA to a maximum value of 1.0).
The fraction of area that is not wet by sweating and hence
available to skin diffusion is therefore (1.0 - WTAREA(I)).
This factor is multiplied by the right side of Equation (1) to
obtain a corrected value of QDIF(I) in the face of sweating.

B. Respiratory Water Loss

Respiratory water losses, as calculated from the original model
result in water losses higher than those recorded experimentally
(Figure 3). As a result, an attempt was made to formulate a new
model describing this process. Water loss due to respiration,
E_R, can be calculated precisely by multiplying the ventilation
rate, V, times the humidity difference between expired, H_{ex},
and inspired air, H_{in}:

$$E_R \text{ (lbs water/hr)} = V \text{ (lbs air/hr)} * (H_{ex} - H_{in}) \text{ (lbs water/lb air)} \quad (3)$$

If this equation is to be useful at various barometric pressures
·it is best to express V in a volumetric rate $(ft^3 \text{ ATP/hr})$ since
the ATP minute volume rather than the mass flow rate tends to
remain constant as ambient pressure changes for a given work
load. Thus:

$$E_R = V_m \text{ } (ft^3 \text{ air ATP/hr}) * \rho_{air,ATP} * (H_{ex} - H_{in}) \quad (4)$$

It has been observed that the ventilation rate is directly pro-
portional to the work rate (Reference 15). If the rate of

RESTING SUBJECTS

(A)

RESPIRATORY WATER LOSS GM/HR

ORIGINAL EQUATION

PROPOSED EQUATION

EXPERIMENT
(Carleton & Welch, 1971)
——○—— 700 mm Hg
——□—— 258 mm Hg
SIMULATION
——●—— 700 mm Hg
——●—— 258 mm Hg

AMBIANT TEMPERATURE °C

(B)

RESPIRATORY WATER LOSS GM/MIN

Original Equation

Proposed Equation

AMBIANT VAPOR PRESSURE mm Hg

EXERCISING SUBJECTS

(C)

RESPIRATORY WATER LOSS GM/HR

ORIGINAL EQUATION

14.7 psi

3.5

PROPOSED EQUATION

3.5   14.7

14.7

3.5

——— Data from Worb (1960)
& Webb(1967)

— — — — Proposed Equation
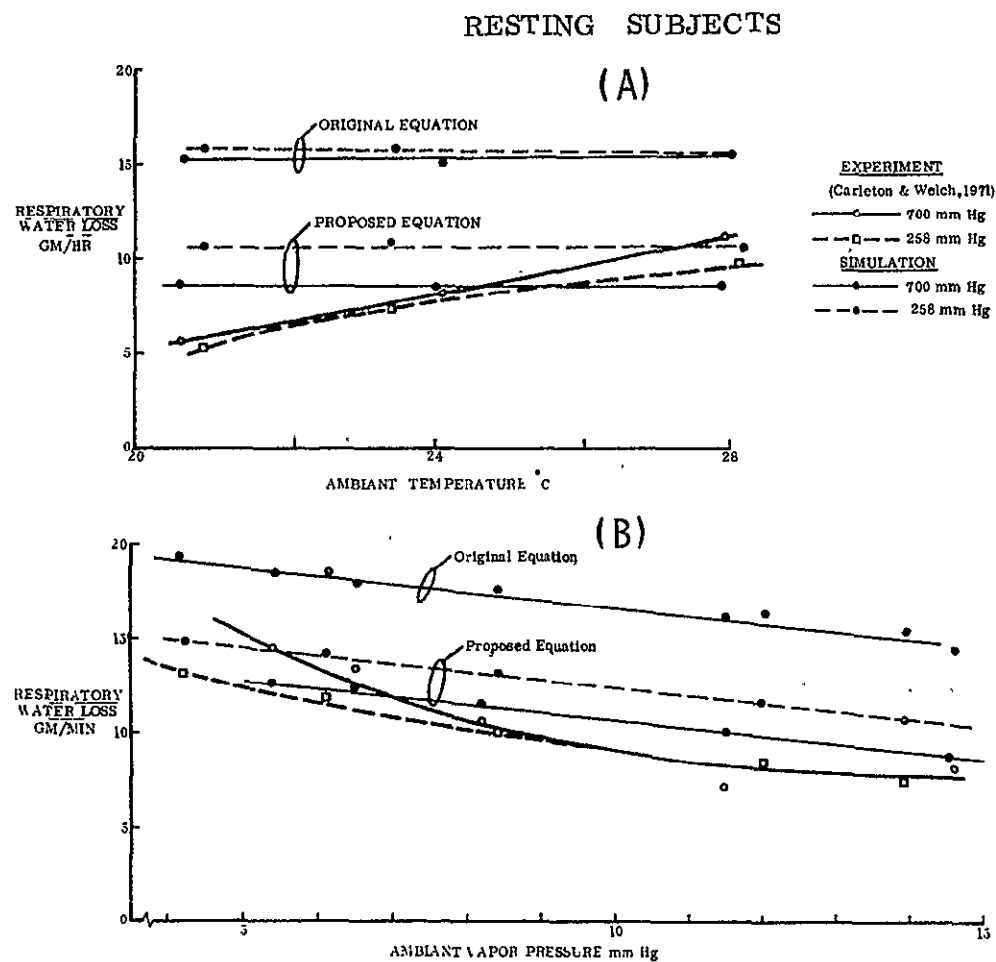
—·—·— Original Equation

METABOLIC RATE BTU/HR

FIGURE 3

Respiratory water loss rate in resting subjects (A and B) and exercising subjects (C) as a function of ambiant temperature, ambiant vapor pressure and metabolic rate. Comparison is made between experimental and simulated results. Results from the original and proposed equation (without the ventilation rate correction term) are compared.

15

metabolism (RM) is in units of BTU/hr, the proportionality constant is 0.415 ft^3 air STP/BTU:

$$V_m = 0.0415 * RM \tag{5}$$

The density of air can be approximated by the ideal gas law,

$$\rho_{air,ATP} = \frac{P}{R * T} * MW = \frac{PCAB * 144 * 28.8}{1544 * (TCAB + 460)} \tag{6}$$

where PCAB and TCAB are expressed in lbs/in^2 and F$^\circ$, respectively. The humidity of a gas is given by the ideal gas law also (Reference 16):

$$H = \frac{p}{P - p} \frac{M_{H_2O}}{M_{air}} \tag{7}$$

where P = barometric pressure, p = vapor pressure of water and M refers to the molecular weight. The vapor pressure for ambient air is the saturation pressure corresponding to the dewpoint or $p = p_s(t_{dew})$. Expired air is not saturated as is sometimes thought but is close to 80% relative humidity (Reference 7, 18). This means that the vapor pressure is 80% of the saturation pressure corresponding to the expired dry-bulb temperature or $p(expired) = 0.8 \ p_s(t_{exp})$. Based on the above the humidity difference between expired and inspired air is found to be:

$$(H_{ex} - H_{in}) = \frac{M_{H_2O}}{M_{air}} \left[\frac{0.8*p_s(t_{exp})}{PCAB - 0.8*p_s(t_{exp})} - \frac{p_s(t_{dew})}{PCAB - p_s(t_{dew})} \right] \tag{8}$$

Saturation vapor pressures as a function of temperature, $p_s(t)$, can be found in most physical chemistry tables and a program that computes this quantity is already part of the thermal model (Subroutine VPPS). The new equation for computing respiratory water losses is obtained by combining Equations 4,5,6, and 8. In FORTRAN notation it appears as:

QR (BTU/hr) = 0.415*PCAB*144.*28.8/(1544.*(TCAB+460))*MR*(HUMEXP -

HUMIN) * 1040.   (9)

where

HUMEXP - HUMIN = 0.622*((0.8*VPP(TEXP)/(PCAB-0.8*VPP(TEXP))-VPPDEW/

(PCAB-VPPDEW)   (10)

The expired air temperature, TEXP, has been given by Reference 17 as a function of inspired air temperature and humidity (derived only for resting conditions):

TEXP = 86.9 + 0.066*TCAB + 57.4*HUMIN   (11)

Equations 9 and 10 differ from the equations they replace only with respect to the estimate of humidity differences. The derivation of the original equation does not appear to be given and is not obvious. The model derived above is based on accepted physiological concepts and physical principles as well as experimental observation.

Figures 3 - 6 show the effects of temperature, pressure, humidity and metabolic rate on respiratory water loss as measured
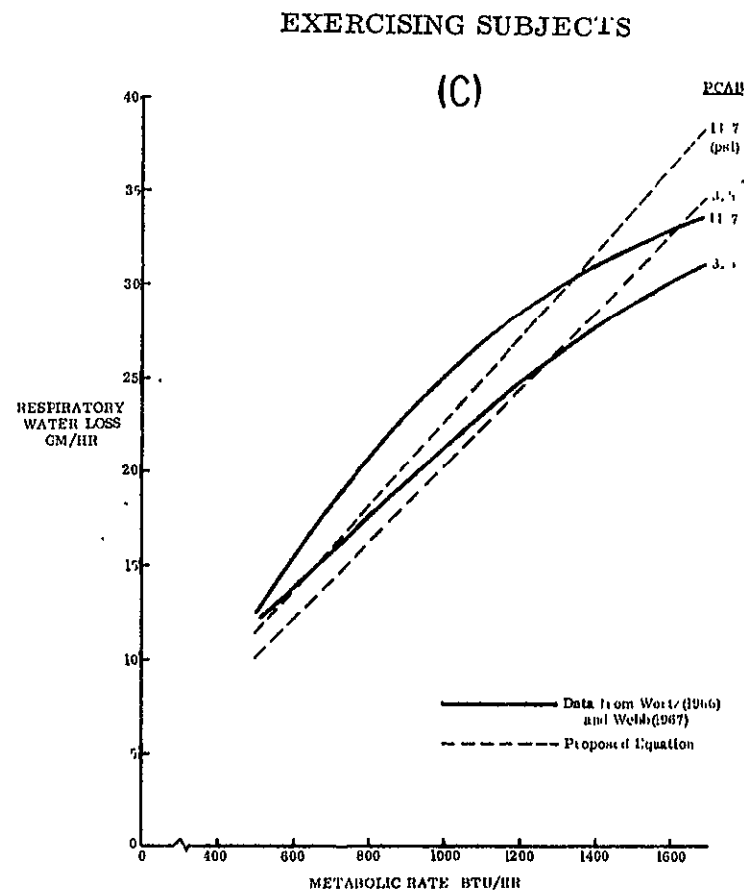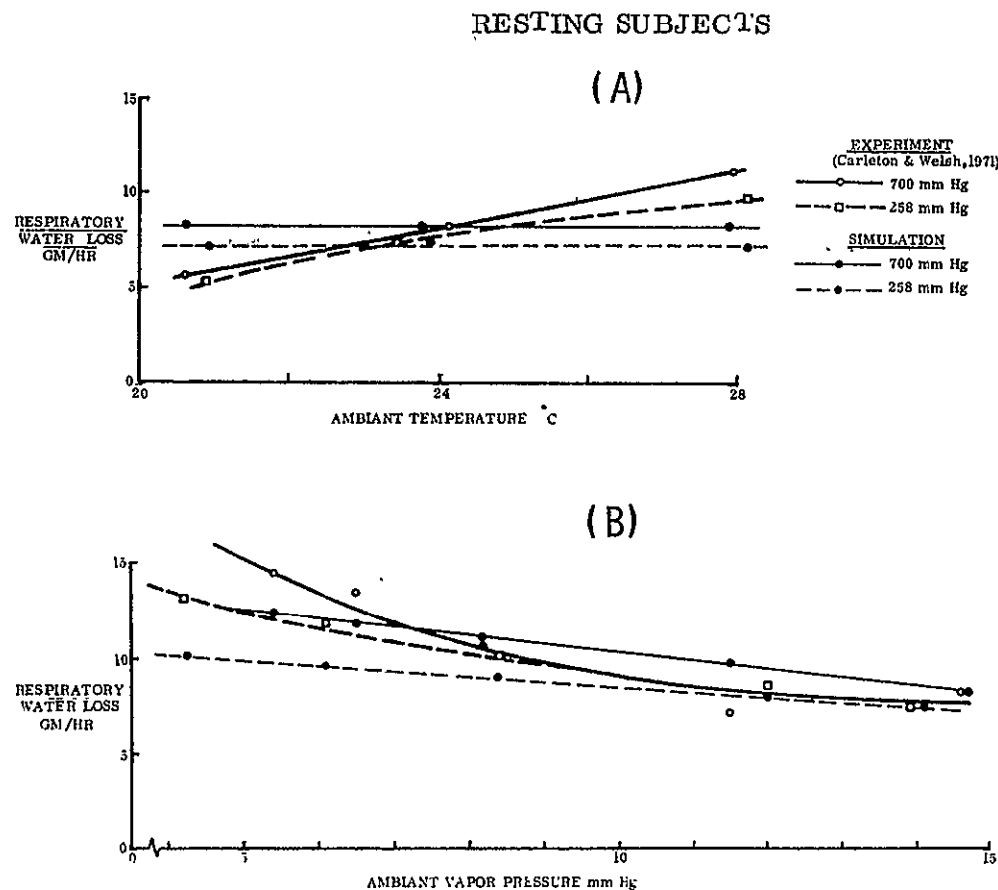
FIGURE 4

Respiratory water loss rate in resting subjects (A and B) and exercising subjects (C). This figure is identical to Figure 3 with the exceptions that results from the original equation are not shown and the propsed equation now includes an empirical correction for decreasing ventilation rate as a function of decreasing barometric pressure.
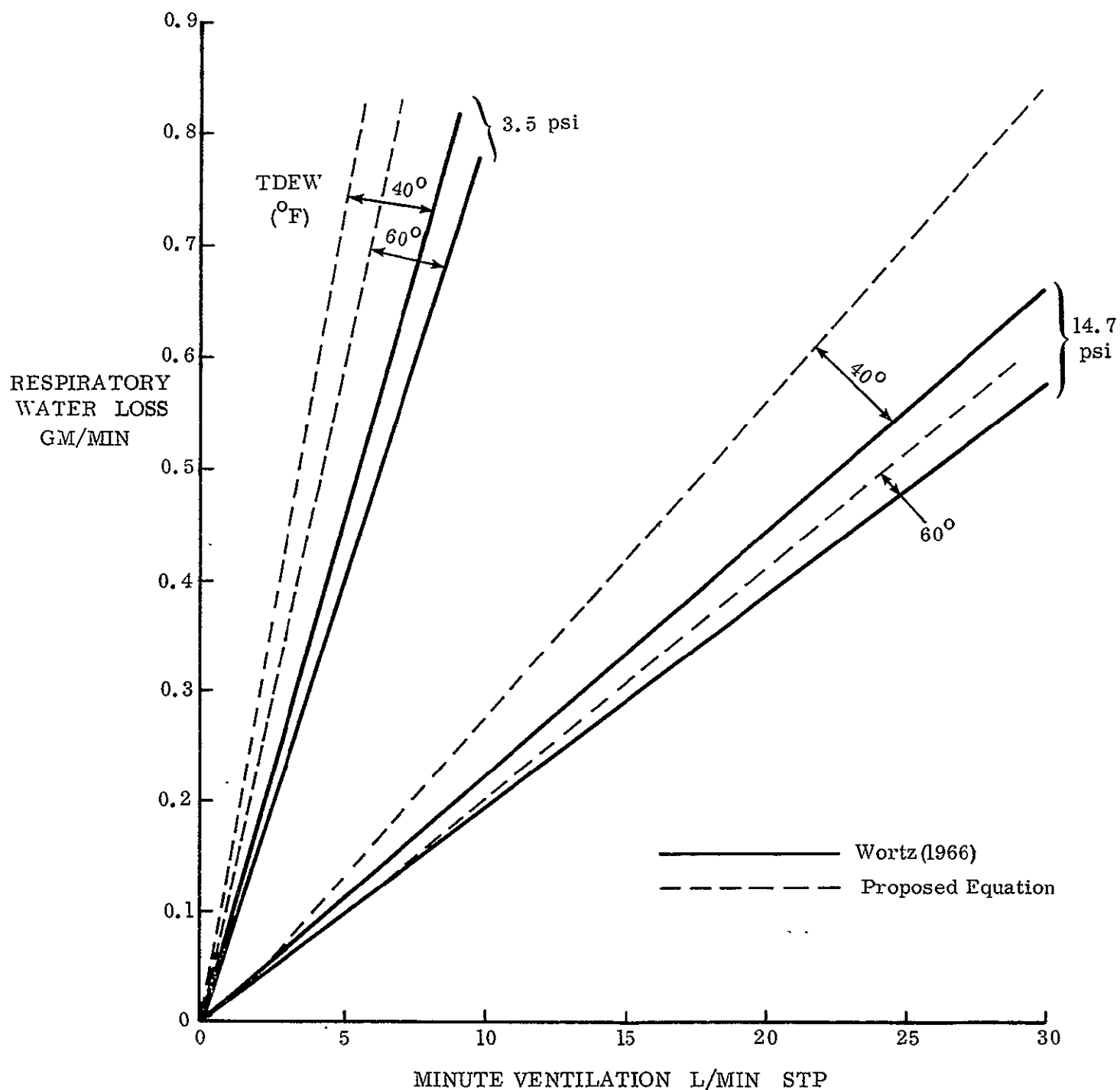
FIGURE 5

Respiratory water loss rate as a function of minute ventilation. Wortz, et al (1966) conclude that the linear relationship shown was the most significant finding of their study. The agreement between the experimental and simulated results (with the ventilation correction included) are shown.
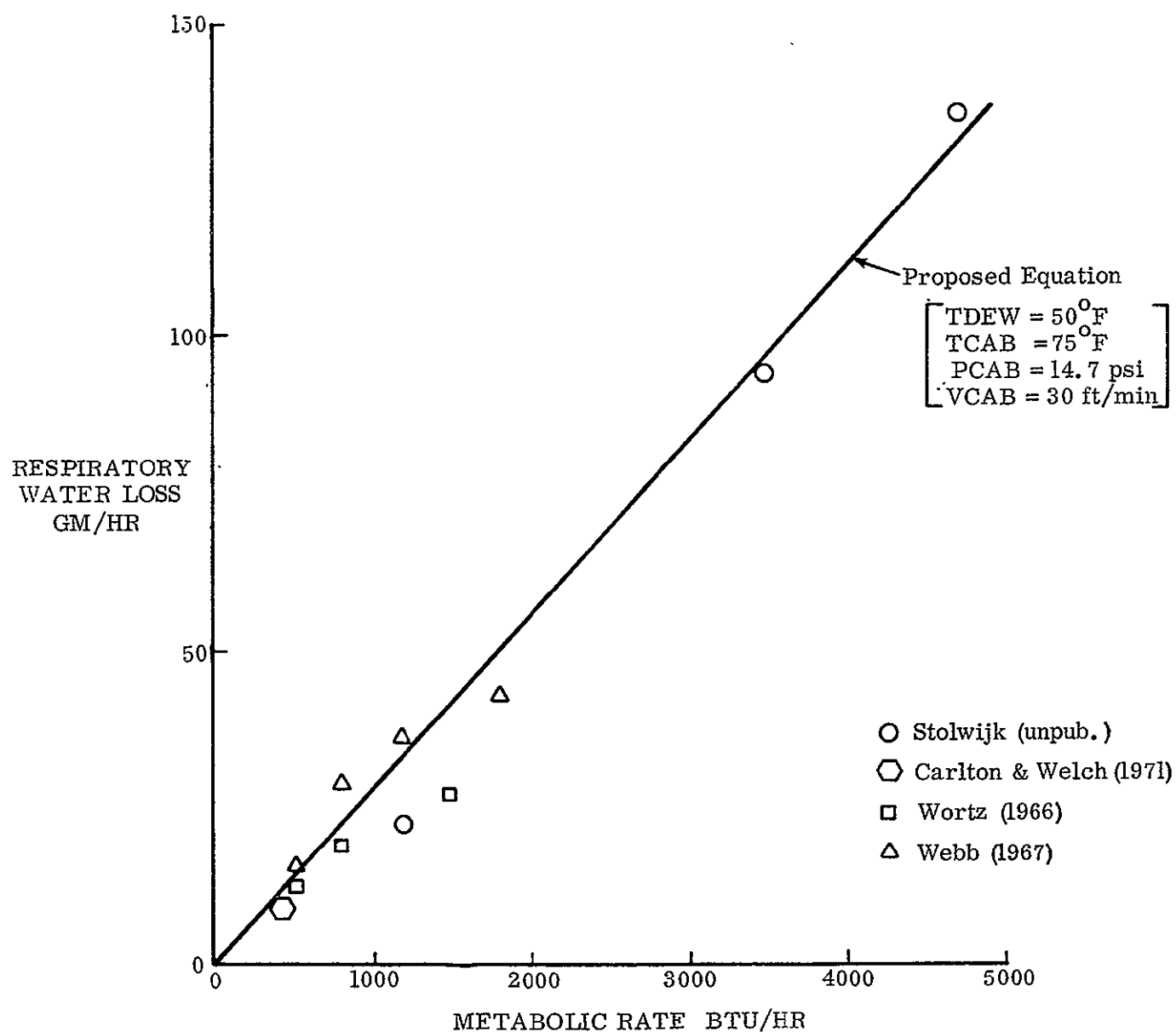
FIGURE 6

Respiratory water loss rate as a function of metabolic rate in exercising
subjects.   This figure summarizes the data previously shown for 1 atm
barometric pressure and extends the range for metabolic rate using
Stolwijk's data.   The proposed equation is in good agreement with the
data of the entire range.

during experimental observation (Reference 13, 18, 19, 20) and
predicted during simulation. Figures 3c, 4c, 5 and 6 were
obtained in exercising subjects while Figures 3a, 3b, 4a and 4b
represent resting individuals. Figures 3 and 4 are identical
with the exception of a ventilation correction factor that will
be discussed below. Figure 3 demonstrates that the proposed
model (Equations 9 and 10) is in closer agreement with experi-
mental data than the original equation. The model correctly
predicts that increasing metabolic rate and decreasing inspired
humidity causes the respiratory losses to increase at approxi-
mately the correct sensitivity to these independent variables.
There is a slight temperature effect on respiratory losses that
the model fails to predict. This is probably due to an
unaccounted for effect of temperature on ventilation rate which
is suggested by the data of Wortz. A fall off in the rate of
water loss with increasing metabolic loads (Figure 3c) observed
in the Wortz and the Webb study does not appear in the study of
Mitchell, et al (Figure 6) nor in the model. However, when the
data of Wortz is plotted versus the minute ventilation
(liter/min STP), which is proportional to metabolic rate, a
linear relationship occurs that is simulated very well by the
model (Figure 5).

Unlike the original equation, the present model is sensitive to
changes in ambient pressure. However, while the data shows that
decreasing pressure causes a reduced respiratory water loss the

proposed model shows an opposite effect (Figures 3a, b, c).
Although this discrepancy is disturbing it demonstrates that
commonly agreed upon physiological concepts are not always
adequate to describe a wide range of situations. In this case
our knowledge of the thermodynamics and mechanics of respira-
tion at low pressures are not sufficiently well known to pro-
duce an accurate model based on physical principles alone.
However, the Wortz study has shown that the decreased respira-
tory losses are due to a decrease in minute ventilation
(liters/min ATP) at decreased ambient pressures. This may be
due to the fact that at reduced pressure less work is required
for breathing and there is less turbulence in the airways. Thus,
by this direct effect on V_m (see Equation 4) the respiratory loss
decreases by as little as 10% at rest to as much as 33% during
medium work loads when ambient pressures change from 14.7 psi
to 3.5 psi. When this empirical observation is used to correct
the proposed equation the resulting behavior of water losses are
in much better agreement with experimental observation (Figures
4a, b, c and 5). Figure 6 illustrates all of the experimental
studies at 1 atm on one graph and compares it with the proposed
model output.

C. Modification of the Sweat Equation

Several changes were made in the equations describing evapora-
tive loss due to sweating. Most of the changes were involved
with nomenclature. The original formulation computed a combined

latent heat of vaporization (QLAT) from two sources: skin

diffusion (QDIF) and sweating, i.e., QLAT(I) = QDIF(I) +

SKINS(I) * SWEAT * 2**(T(I) - TSET(I))/4. The last term on the

right describes the rate of sweating. Stolwijk and his col-

leagues (Reference 6,21) suggested the following revision which

we have incorporated: SKINS(I)*SWEAT*EXP(T(I) - TSET(I))/18.

We have also divided the above equation into two segments that

permits the separate computation of the sweat and diffusion

components and also takes into account that diffusion can

approach zero as the amount of sweating increases, thus:

   QLAT(I) = QDIF(I) + QSWT(I)

           = evaporative heat loss due to diffusion and sweating

where,

   QSWT(I) = SKINS(I)*SWEAT*EXP(T(I) - TSET(I))/18.

and,

   QDIF(I) = QDIF(I)*(1.0 - WTAREA(I))   (see Section 3-A)

WTAREA(I), the fraction of surface I that is wet (defined in

Equation (2)), is not permitted to be greater than 1.0 and   .

QLAT(I) is not permitted to have a value greater than EMAX(I).

However, dripping of sweat occurs if QLAT(I) is greater than

EMAX(I) and this amount (DRIP) is computed and printed. The

whole body sum of respiratory (QR), diffusional (QD) and sweat-

ing (QSWEAT) heat losses are given by the following definitions:

$$QD \quad = \sum_{I=1}^{10} QDIF(I) \qquad (\text{skin diffusion only})$$

$$QSWEAT \quad = \sum_{I=1}^{10} QSWT(I) \qquad (\text{sweating only})$$

$$QEVAP \quad = QR + QD + QSWEAT \qquad (\text{total evaporative losses})$$

QEVAP replaces TOTL from the original program and has the identical definition.

Recently, Stolwijk has proposed that the model describing the regulation of rate of local sweat secretion should be expanded to include a reabsorption (or leakage) term (Reference 22). In accord with this suggestion the sweating equation has been modified by including a term R1 that subtracts its value from the local sweat rate, i.e.,

$$QSWT(I) = SKINS(I)*(SWEAT*EXP(T(I) - TSET(I))/18. - R1)$$

This feature is still being tested and the normal value of R1 is set to zero. With the equation in this form it is possible to assign various values to R1 and study the resulting behavior of the model.

4.0 PARAMETER ESTIMATION STUDY

One of the prime purposes of this model is to accuracely predict the thermoregulatory behavior of man in various environments and activities. For example, it is very desirable to simulate sweating

behavior and skin temperatures during exercise or at low ambient pressure. As far as can be determined, except for the work of Stolwijk with the simplified version of his model, the present steady-state or transient model has never been properly validated and tested against recorded experimental observation. The present report (Section 3) includes the initial phase of such an effort. Additional work is now in progress on the sweating and shivering features of the model and will be documented in future progress reports.

There are basically only three easily measurable physiological properties that have a major influence on the thermoregulatory system. These are: 1) temperature (skin, rectal, oral, esophogel, tympanic, etc.); 2) evaporative water loss (respiratory, skin diffusion, and sweating) and 3) blood flow (cardiac output, skin flow, muscle flow, etc.). For the past few months a considerable effort has been made to collect experimental reports in which these variables have been measured under a variety of test conditions. Preliminary simulations of the steady-state model have indicated that the model is in basic agreement with the data, but more work is necessary to improve its behavior, especially with regard to sweating and shivering regulation. The first attempts to "tune" the model would involve adjusting certain parameters. To facilitate this effort the model has been modified so that the process of parameter estimation can be performed at the normal initialization step prior to each run without having to change the program itself. At this time four parameters can be adjusted

merely by typing in the desired value at the start of the simulation. These have been given the designation R1, R2, P1 and P2 and have the following significance:

R1 = term that reduces the heat loss due to sweat and represents reabsorption of sweat back into the body (normal value = 0.0 BTU/hr)

R2 = multiplier of the SWEAT signal that effectively changes the values of the sweat parameters CSW and SSW by the same proportion (normal value = 1.0)

P1 = multiplier of the heat transfer coefficient for thermal conduction (HC and HC1) between the skin-air interface (normal value = 1.0)

P2 = multiplier of the heat transfer coefficient for radiation (HR) exchange with the environment (normal value = 1.0)

The values of these parameters are internally set to the normal values listed above unless they are changed in accord with instructions in the User's Guide (Reference 3). As an example, if P2 is set to 1.1, the value or the radiation heat transfer coefficient HR would be increased by 10%. An example of the effects of these parameters on the behavior of the system is shown in Figure 7 where experimental data is plotted together with simulation runs for four cases. Curve A represents the present model output prior to any attempt to adjust parameters. It is obvious that a closer agreement with the data would be desirable. Examples of the types of parameter adjustment that can be made are illustrated by curves B, C, and D. It is expected that further modifications of this type will be made to improve the efficiency of the parameter estimation procedure.

RUN	R_1	R_2	P_1	P_2
A	0	1.0	1.0	1.0
B	2000	1.0	1.0	1.0
C	2000	0.25	1.0	1.0
D	2000	0.25	1.2	1.2

●——— REFERENCE 24

TOTAL
EVAPORATIVE
LOSS
GM/HR

AMBIENT TEMPERATURE ^{0}F

MODEL INPUT
PARAMETERS
RM = 340 BTU/hr
QBASAL = 283 BTU/hr
UEFF = 0%
POS = 2
TW = TCAB
TDEWC = 35%RH
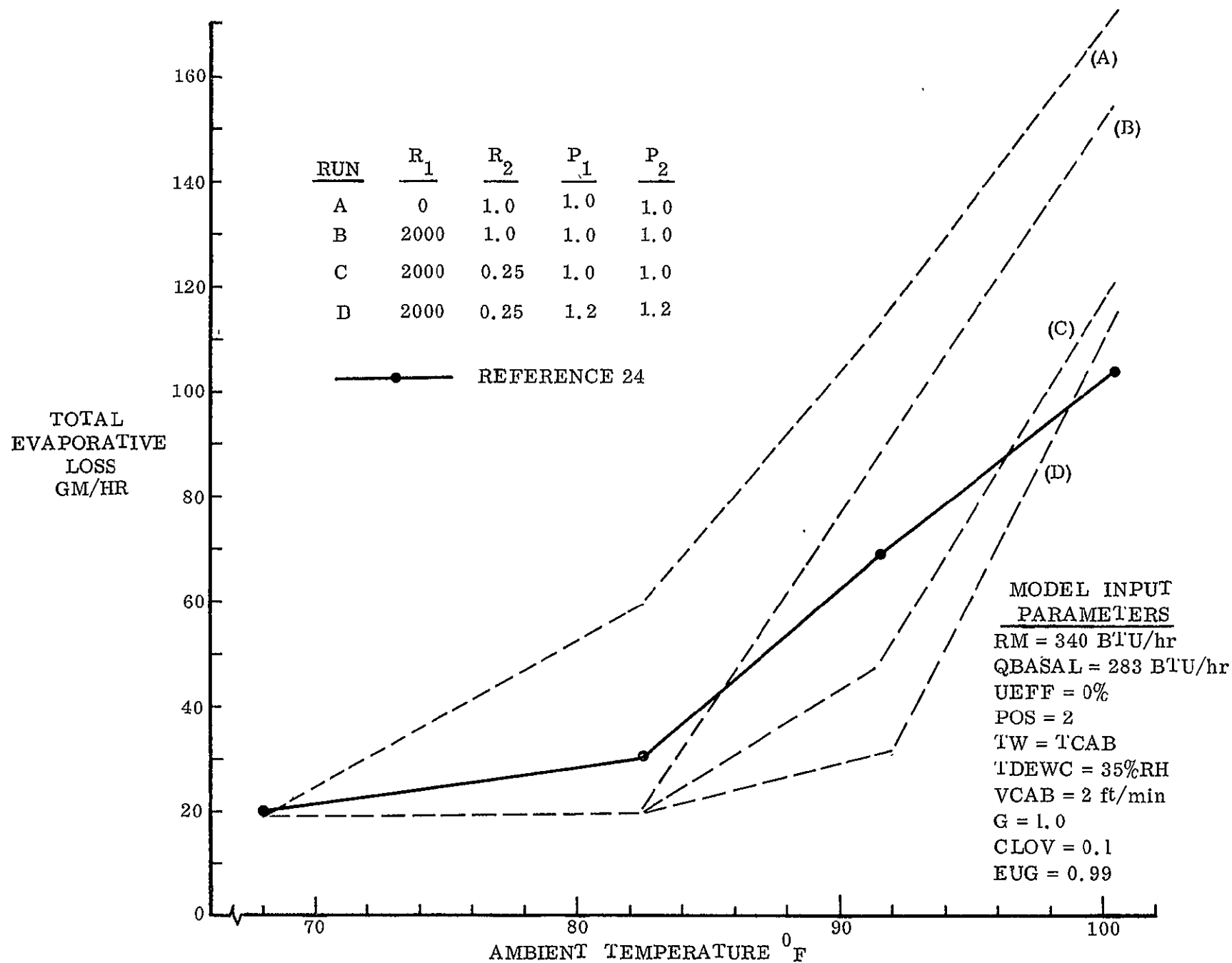VCAB = 2 ft/min
G = 1.0
CLOV = 0.1
EUG = 0.99

FIGURE 7

Effect of ambient temperature on evaporative loss rate in resting subjects as recorded experimentally
and predicted with the model. Four parameters that effect sweating (R1 and R2) and insensible heat
loss (P1 and P2) have been varied to show their effect on evaporative loss.

5.0 RECOMMENDATIONS FOR FURTHER RESEARCH

During the course of this study certain deficiencies have been re-
vealed, both in the model itself as well as gaps in available data
on thermoregulatory behavior. This has pointed the way to defining
and clarifying computer simulation and laboratory experiments. The
following list of suggested areas of research is a result of inter-
action between the systems analysis and a review of experimental
literature. It is somewhat random and by no means complete.

a) Although there is sufficient data available for evaporative
loss rates at rest under various conditions of pressure, temperature,
etc., there have been no corresponding studies performed during exer-
cise at low ambient pressure. Inasmuch as all of the manned space
missions have utilized pressures much below atmospheric where the
evaporative processes are enhanced, this becomes a serious deficiency.

b) Skin blood flow becomes an important variable in determining
skin temperatures and therefore inputs to the hypothalamic controller
especially during exercise. We are not aware of any studies simul-
taneously measuring skin and muscle blood flow responses to exercise
where it is not obvious how the competing demands for blood by the
oxygen-starved muscle and the need for increased skin flow for removing
metabolic heat are resolved.

c) The physical characteristics of the sweat film and wetted
skin area appears to be different in 1-g and in weightlessness. This
might have significant implications on the sweating mechanism inasmuch
as it is now known that sweat suppression occurs as the skin becomes

wet. Thus, the sweating phenomena and associated mechanisms occurring during weightlessness needs to be studied carefully.

d) The interplay of natural and forced convection is not well understood, especially in certain mixed regions of free air velocity. This interaction can be fruitfully studied by performing certain crucial experiments in 1-g and repeating them in weightlessness where free convection does not occur. The results from such a study would have implications not only for physiological thermoregulation, but for non-biological heat transfer processes as well.

e) Relative air velocity over the body is a function not only of the mean air velocity itself, but also of clothing, body position relative to wind direction, type of activity and level of activity. It is important to clarify these effects on the film coefficient for convection and evaporation.

f) The present study has revealed that the heat transfer characteristics of the respiratory process are not well understood. More research is needed to clarify the mechanism that causes the ventilation rate to decrease at decreased pressures. Also lacking is a deterministic model that can predict expired air temperature and humidity. Respiratory water loss is fortunately not very significant during high levels of activity, but can become significant during situations such as bed rest and low ambient humidities.

g) The thermoregulatory model contains many parameters that have varying effects on overall thermoregulatory behavior. One of the unique advantages of mathematical models is that they can provide

a rapid means of estimating the sensitivity of these input terms on output function. It is recommended that such a sensitivity analysis be performed.

h) A large body of literature exists documenting evaporative loss rates during various experimental conditions. It is recommended that an effort be made to validate the model with this data using parameter estimation techniques outlined in Section 4. This is particularly important during cases of exercise where sweat rates are high and the model's accuracy is uncertain.

i) The Skylab medical experiments have provided sufficient data to perform a rough estimate of evaporative loss rates. The thermo-regulatory model is capable of simulating the conditions of these space missions and predicting evaporative loss rates also. It is recommended that these separate experimental and simulation analyses be performed and compared. This would provide not only the best obtainable estimates for evaporative loss during space flight, but would also be a means of validating the model. A preliminary analysis of this type, proving its feasibility, has already been performed and documented (Reference 23).

REFERENCES

1. Smith, S.M. 1973. Simplified 41-Node Stolwijk Metabolic Man Model (1108 Version), TIR 741-MED-3011, General Electric Company, Space Division, Houston Programs.

2. Smith, S.M. 1973. Simplified 41-Node Stolwijk Metabolic Man Model (Sigma 3 Version), TIR 741-MED-3013, General Electric Company, Space Division, Houston Programs.

3. Leonard, J. I. 1974. User's Instructions for the 41-Node Thermoregulatory Model (Steady-State Time-Share Version), TIR 741-MED-4015, General Electric Company, Space Division, Houston Operations.

4. Smith, S.M. 1972. Sigma 3 Steady-State Version of Lockheed Program, TIR 741-MED-2011, General Electric Company, Houston Programs.

5. Carnahan, B., Luther, H.A., and Wilks, J.O. 1969. "Applied Numerical Methods", John Wiley & Sons, Inc., New York.

6. Stolwijk, J.A.J. 1971. A Mathematical Model of Physiological Temperature Regulation in Man, Final Report, NASA Contract NAS 9-9531.

7. Stolwijk, J.A.J. 1970. Mathematical Model of Thermoregulation, Chapter 48 in "Physiological and Behavioral Temperature Regulation", Hardy, J.D., Gagge, A.P., and Stolwijk, J.A.J. (Ed), Charles C. Thomas Cd., Springfield, Ill.

8. Stolwijk, J.A.J. 1969. Expansion of a Mathematical Model of Thermoregulation to Include High Metabolic Rates, Final Report, NASA Contract NAS9-7140.

9. Morgan, L.W., Collett, G., and Cook, D.W., "Computer Program Documentation: 41-Node Transient Metabolic Man Program", LEC/672-23-030031, NASA Contract NAS9-5384, Lockheed Electronics Company, Houston Aerospace Systems Division.

10. Parker, J.F. and West, V.R. (Ed) 1973. "Bioastronautics Data Book", 2nd Edition, NASA SP-3006, National Aeronautics and Space Administration, Washington, D.C.

11. McAdams, W.H. 1954. "Heat Transmission", McGraw Hill, New York.

12. Chapman, A.J. 1967. "Heat Transfer", 2nd Edition, MacMillan Co., New York.

13. Carleton, W.M. and Welch, B.W. 1971. "Fluid Balance in Artificial Environments: Role of Environmental Variables", Environmental Sciences Division, USAF School of Aerospace Medicine, Brooks'AFB, Texas, Contract NASA/DOD PRT-7493-6.

14. Gagge, A.P. 1972. Partitional Calorimetry in the Desert, in "Proceedings Symposium Physiological Adaptations: Desert and Mountains", Academic Press, New York.

15. Fanger, P.O. 1970. "Thermal Comfort", McGraw Hill, New York.

16. Perry, J.H. 1952. "Chemical Engineers Handbook", McGraw Hill Co., New York.

17. McCutchan, J.W. and Taylor, C.C. 1951. Respiratory Heat Exchange with Varying Temperature and Humidity of Inspired Air, Journal of Applied Physiology, 4:121-135.

18. Mitchell, J.W., Nadel, E.R., and Stolwijk, J.A.J. (unpublished), Respiratory Weight Losses During Exercise, J.B. Pierce Foundation Laboratory, 290 Congress Avenue, New Haven, Connecticut 06519

19. Webb, P. 1967. "Human Water Exchange in Space Suits and Capsules", NASA CR-804, National Aeronautics and Space Administration, Washington,D.C.

20. Wortz, E.C., Diaz, R.A., Green, F.H., Sanborn, W.G., Edwards, D.K., Prescott, E.J. and Scherer, G.R. 1966. "Reduced Barometric Pressure and Respiratory Water Loss", SAM TR 66-4, USAF School of Aerospace Medicine, Brooks AFB, Texas.

21. Nadel, E., Bullard, R.W. and Stolwijk, J.A.J. 1971. Importance of Skin Temperature in the Regulation of Sweating. Journal of Applied Physiology, 31:80-87.

22. Stolwijk, J.A.J. and Nadel, E.R. 1973. Sweating Response in Human Thermoregulation. In "Regulation and Control in Physiological Systems", Iberall, A.S. and A.C. Guyton (Ed), Instrument Society of America, Pittsburgh, Pa.

23. Croston, R.C., Fitzjerrell, D.G. and Leonard, J.I. 1974. Study Report on Skylab Medical Experiments Integrated Data Analyses. TIR 741-MED-4009, General Electric Company, Space Division, Houston Operations.

24. Hardy, J.D. and Stolwijk, J.A.J. 1968. "Response of Man to Thermal Transients". In AGARD Thermal Problems in Aerospace Medicine, N69-25060, p. 105-127.